Looking for Antiquarks in Nuclei

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Introduction

Recent experiments carried out at Fermi National Accelerator Laboratory's 800-GeV proton synchrotron have stirred the nuclear physics community in recent years by revealing unexpected phenomena in the realm of antiquark behavior. Through these experiments, our team has taken a pioneering step into a new field that combines objectives of interest to nuclear physicists with the techniques and framework of high-energy physics.

This paper describes the work that lead to this experimental effort, and it highlights the main results from Experiment 772 (E772), which began our search for antiquarks. This experiment was the beginning of a very successful collaboration that lead the same core personnel to participate in two additional experiments. The success of this collaboration is evidenced in the impact of the data on the nuclear physics community. In 1998, this work was awarded the prestigious Tom W. Bonner Prize, which recognizes outstanding experimental research in nuclear physics.

Nuclear Physics and Quarks

We all know that the aspects of nuclear physics that touch most people's lives—bombs and nuclear reactors—were invented in the 1940s and 1950s long before anyone knew about quarks and gluons. Similarly, the nuclear physics known prior to the first quark model (1964) was sufficient to understand the mechanisms for energy generation in the sun and stars. Through the development of a combination of phenomenological models, including the Nobel-Prize winning nuclear shell model, the beautiful and varied properties of nuclei could be understood at a quantitative level—all before quarks were sparkles in the eyes of their theoretical creators, Murray Gell-Mann and George Zweig, and long before the experimental discovery of quarks in 1970.

In spite of the successes of quarkless nuclear physics, in the late 1970s and early 1980s quarks, gluons, and the underlying theory of their interactions, known as quantum chromodynamics (QCD), had become so well established in particle physics that nuclear physicists were asking, "What's in it for us?"

Nucleons Under the Microscope

The mystery of quarks is still that one doesn't "see" them one at a time. They always come in threes, or baryons, of which protons and neutrons are the best known examples, or in pairs of quarks and antiquarks, or mesons, the particles whose exchange between neutrons and protons binds them into nuclei. Collectively baryons and mesons are known as hadrons. An excellent expression of this dichotomy is found in the words of the famous Russian theorist Y. L. Dokshitzer, "Quarks and gluons are the truth, but hadrons are the reality." Figure 1 illustrates the "reality" of the proton in low and high resolution pictures.

Looking for Quarks Inside Nuclei

In the early 1980s physicists were looking for an experiment that would definitively demonstrate that nuclei were more than systems of neutrons and protons bound by meson exchange—nuclei, too, would exhibit effects explainable only in terms of the truly elementary particles, quarks. The dilemma was concisely stated in an unpublished talk at the International Nuclear Physics Conference in Florence, Italy in 1983. "They [quarks] are like the Mafia in Sicily. They may be hard to spot, but you just know that they are there somewhere."

The answer to this dilemma arrived in 1983 with the publication of the now famous European Muon Collaboration (EMC) effect[1]. The EMC used 200-GeV muon beams at the European Laboratory for Particle Physics (formerly the *Centre Européenne pour la Recherche Nucléaire*, or CERN) Super Proton Synchrotron to carry out a higher-energy version of the same experiment that had led to the Nobel-Prize winning discovery of quarks at the Stanford Linear Accelerator Center (SLAC) electron accelerator. It takes an average of 8 MeV to remove a nucleon from a nucleus, and the CERN experiment used beams some 25,000 times greater in energy. A rough analogy might be a bowling ball running headlong into a bowling pin: Surely it doesn't matter whether or not the pin has been taped to the floor! Similarly, or so the experimenters presumed, it couldn't matter whether the CERN experiment used a hydrogen (deuterium) target, where the quarks are in free nucleons, or a more convenient target such as iron, where the quarks are bound in nuclei. Fortunately, the EMC group took data for both kinds of targets. The results were surprising. When the EMC compared the data, the ratio of scattering probabilities from iron and deuterium was very significantly different from unity. It mattered whether quarks were in free nucleons or bound in nuclei! This result electrified the nuclear and high-energy physics communities. Within two years of the EMC publication there were more that 300 theoretical papers written about how the data might be understood.

Antiquarks Inside Nuclei

The problem, of course, was that there was only one EMC effect, a relatively small data set that could be reproduced theoretically by many different mechanisms. What was needed was a different experiment. Many of the theorists working in this area hit upon the Drell-Yan (DY) process as the answer. In simplest terms, the DY process is quark-antiquark annihilation—the quark and antiquark are contained in two different hadrons which collide. This annihilation results in the production of a pair of leptons with

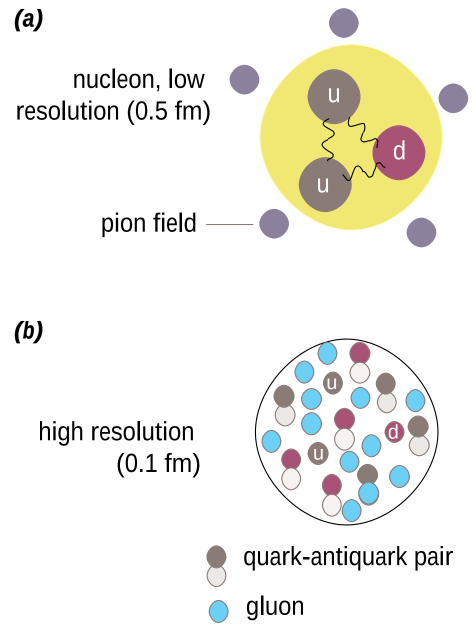

***Fig. 1** Low (a) and high (b) resolution illustrations of the proton. The basic properties of the proton, such as electric charge, are determined by two "up" quarks of charge +2/3 and one "down" quark of charge -1/3. The pion field, which provides the longest-range part of the two-nucleon interaction, consists of pairs of quarks and antiquarks. For example, the π^+ is composed of an up quark (+2/3) and an antidown quark (+1/3).*

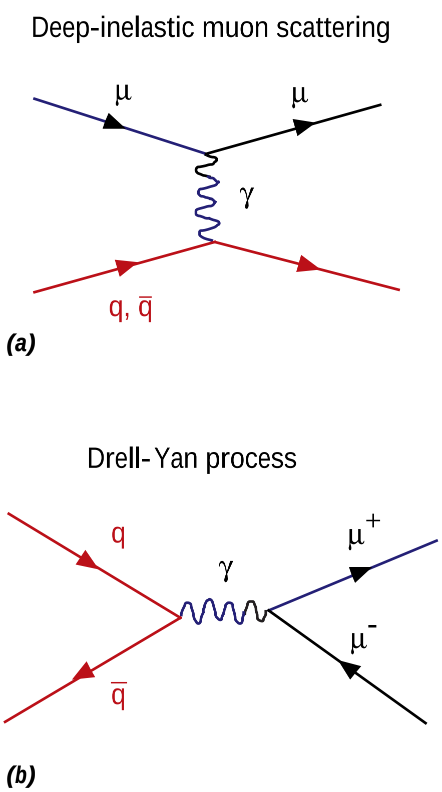

Fig. 2 Feynman graphs for two related high-energy electromagnetic processes. In (a), a high-energy muon (top left) collides with a quark or antiquark in the target. As the reaction proceeds to the right in time, the momentum of the muon scattered to the upper right is measured in a spectrometer. From the initial and final muon momenta, the energy transferred to the quark can be inferred. In the DY process, (b), a quark from one hadron annihilates with an antiquark from a second hadron, producing a virtual photon which subsequently decays into a pair of muons. Here, by energy conservation, a measurement of the final muon momenta is sufficient to reconstruct the original colliding quark and antiquark momenta.

very large mass. The Los Alamos Subatomic Physics Group (P-25) was introduced to this process in the early 1980s in a seminar given by theorist Gerry Miller of the University of Washington.

Figure 2 shows the relation between deeply inelastic lepton scattering (DIS), the original quark-discovery reaction, and its close cousin, the DY process. The DY process was "discovered" theoretically in 1970, near the time of the first DIS experiments at SLAC. It was verified experimentally at Fermilab and CERN in the late 1970s only after the experimental techniques were developed for measuring this process, which has a very small cross section in the presence of huge backgrounds.

Our contributions began around 1985–86. We discovered that a measurement of the nuclear dependence of the DY process at the level of precision of the EMC effect had never been made. We also discovered that the theoretical issues connected with a quantitative understanding the DY process had largely been resolved in the early 1980s. Thus, it was time for a new experiment. But not just any DY experiment would do. The experimental conditions had to be arranged for maximum sensitivity to antiquarks in the target. In brief, this required a beam of high-energy protons—not pions or antiprotons—and a spectrometer to detect the highest-energy, most forward-going dimuons. Fortunately, these conditions could be met using an existing spectrometer and beamline at Fermilab. In 1986 a bare-bones group consisting of Jen-Chieh Peng, Gerry Garvey, and Joel Moss from Los Alamos National Laboratory and Chuck Brown and Bob McCarthy from a previous Fermilab collaboration concocted a proposal, which eventually became the now famous E772. Its title was, "Study of the nuclear antiquark sea via proton-induced dimuon production." These collaborators managed to rebuild, reconfigure, and successfully operate the relic Fermilab spectrometer to accomplish the required precision measurement—a significant achievement that, from proposal to publication, took only three years.

Where are the Nuclear Pions?

The E772 collaboration made a precision comparison of DY muon-pair production on targets of deuterium, carbon, calcium, iron, and tungsten. The surprising result was that there is almost no difference in the antiquark density in the heaviest targets compared to deuterium, quite unlike what was found for quarks in the EMC experiment. From almost any conventional view of nuclei, in which nucleons are bound by the exchanges of mesons, this is an enigma. After all, in quark-model terms, mesons are quark-antiquark states. So what happens to the antiquarks in nuclei? There are many ways to quantify this dilemma. Suffice it to say here that conventional meson exchange naturally leads to excesses of antiquarks in heavy targets in the range of 5–20%. The E772 data, on the other hand, are inconsistent with more than 2–4% enhancement.

Publication of the E772 results lead to considerable theoretical hand wringing. In 1993, George Bertsch, Leonid Frankfurt, and Mark Strikman addressed the issue in an article entitled ”Where are the Nuclear Pions?” To illustrate the level of debate, a few months later the eminent nuclear theorist Gerry Brown and his collaborators published a rebuttal of sorts, entitled provocatively, “Where the Nuclear Pions Are!” Their explanation, based on a scale change associated with partial restoration of chiral symmetry, has not gained a large following. It is fair to say that much of the nuclear physics community is still mystified over the E772 data.

The Pion Field of the Proton

The newest contribution to our understanding of the E772 data has occurred only recently as a result of experiments performed in the 1990s. The most significant of these experiments was Fermilab E866, an effort lead by P-25 scientists Gerry Garvey, Pat McGaughey, and Mike Leitch in collaboration with scientists from other Los Alamos National Laboratory groups, Abilene Christian University, Argonne National Laboratory, Fermilab, Georgia State University, the Illinois Institute of Technology, Louisiana State University, New Mexico State University, Oak Ridge National Laboratory, Texas A&M, and Valparaiso University. The major results from this experiment were discussed in detail in a previous research highlight.[2]

In summary, the E866 collaboration employed the same reaction as performed eight years earlier by E772, the venerable DY process. This time, the goal was to find a telltale signature of the proton’s pion field. In simplest terms, that signature is the presence of an excess of antidown quark caused by the virtual emission of a pion in the process $p \rightarrow n + \pi^+$. The DY process easily picks out the extra antidown quark. The experiment was carried out by making a precision comparison of DY production from both proton and neutron targets. Of course neutrons are not stable, so one uses the best substitute, deuterium, which contains a neutron and a proton. The experiment made use of two 20-cm-long liquid targets containing hydrogen and deuterium, and a significantly upgraded version of the E772 spectrometer.

The result of the E866 measurement (consistent with two previous but less precise experiments) is that the excess of antidown quarks with respect to antiup quarks in the proton is very nicely accounted for by the proton’s pion field. This is an important milestone in the study of the quark structure of nucleons as it is the most compelling evidence to date of a strong link between the low resolution (meson-nucleon) and high resolution (quark) pictures of the nucleus (Fig. 1).

Where Do We Go from Here?

Since the characteristic signature of the pion field has been so clearly seen at the quark level, the lack of excess antiquarks in nuclei seems even more perplexing. Where do we go from here? The standard answer for an experimentalist is, of course, "more experiments." In fact, an experiment is already being prepared at Thomas Jefferson National Laboratory. There, experimenters will try to detect the pions responsible for nuclear binding by knocking them out of light nuclei using 4-GeV electrons. Will the pions be there in the substantial numbers indicated by the very sophisticated nuclear models developed in recent years? The nuclear physics community will surely speculate, but only time—and experimental data—will tell.

References

[1] J. J. Aubert, G. Bassompierre, S. K. H. Beck, C. Best, E. Bohm, X. Debouard, F. W. Brasse, C. Broll, S. Brown, J. Carr, R. W. Clifft, J. H. Cobb, G. Coignet, F. Combley, G. R. Court, G. Dagostini, W. D. Dau, J. K. Davies, Y. DeClais, R. W. Dobinson, U. Dosselli, J. Drees, A. W. Edwards, M. Edwards, J. Favier, M. I. Ferrero, W. Flauger, E. Gabathuler, R. Gamet, J. Gayler, V. Gerhardt, C. Gossling, J. Haas, K. Hamacher, P. L. Hayman, M. Henckes, V. Korbel, U. Landgraf, M. Leenen, M. Maire, H. Minssieux, W. Mohr, H. E. Montgomery, K. Moser, R. P. Mount, P. R. Norton, J. McNicholas, A. M. Osborne, P. Payre, C. Peroni, H. Pessard, U. Pietrzyk, K. Rith, M. Schneegans, T. Sloan, H. E. Stier, W. Stockhausen, J. M. Thenard, J. C. Thompson, L. Urban, M. Villers, H. Wahlen, M. Whalley, D. Williams, W. S. C. Williams, J. Williamson, and S. J. Wimpenny, "The Ratio of the Nucleon Structure Functions F2N for Iron and Deuterium," *Physics Letters B* 123, 275 (1983).

[2] M. J. Leitch, M. Brooks, T. Carey, G. Garvey, D. Lee, P. McGaughey, J. Moss, B. Park, J.-C Peng, P. Reimer, W. Sondheim, N. Thompson, D. Isenhower, M. Sadler, R. Towell, D. Geesaman, S. Kaufman, M. Makins, B. Zeidman, C. Brown, B. Cooper, G. Petit, X. He, B. Lee, D. Kaplan, P. Kirk, Y. Wang, Z. Wang, M. Beddo, T. Chang, G. Kyle, V. Papavassiliou, J. Webb, T. Awes, P. Stankus, G. Young, C. Gagliardi, B. Tribble, E. Hawker, D. Koetke, and P. Nord, "NUSEA—Measurement of the Asymmetry in the Light-Antiquark Nucleonic Sea," *Physics Division Progress Report, January 1, 1995–December 31, 1996,* Los Alamos National Laboratory Report LA-13355-PR (1997), pp. 96–99.